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Comprehensive comparison between sic-mosfets and si-igbts based electric vehicle traction systems under low speed and light load

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Abstract

In this paper, the performance of both SiC-MOSFETs and Si-IGBTs based electric vehicle (EV) traction systems under low speed and light load are investigated and compared comprehensively, particularly from efficiency point of view. Both conduction loss and switching loss of SiC-MOSFET are analyzed and modeled taking temperature effect into account. Such methodology yields more accurate prediction of losses. The temperature distributions of the two inverters with the same heat sink are described by ANSYS finite element analysis (FEA), respectively. This paper first explore that the motor has extreme high efficiency under low speed and light load when it is driven by SiC-MOSFETs based inverter, which thanks to higher switching speed of SiC MOSFETs. Experimental results show that the SiC-based traction system has higher system efficiency compared to the Si-based traction system under low speed and light load. And experimental results also give more confidence of the losses models of SiC MOSFETs.

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Keywords: SiC-MOSFETs; Si-IGBTs; Electric vehicle traction systems; Losses

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1. Introduction

Electric vehicle (EV) traction systems are undergoing significant changes with the application of wide band-gap semiconductor devices, such as SiC or GaN MOSFETs, according to their increased high switching speed, junction operation temperature, low thermal resistance, etc. Previous researches have studied the superior characteristics of SiC MOSFETs compared to Si counterparts [1-2]. Based on the semiconductor physics properties, including bandgap energy, critical electric field, saturation velocity and thermal conductivity, high switching speed, low power loss, high temperature stability were investigated respectively.

Prototype inverter systems equipped with SiC-MOSFETs demonstrated a marked loss reduction compared with that of a conventional inverter system with Si power devices. The efficiency improvement of SiC-MOSFETs based inverter system is prominent, many research works focus on SiC MOSFET's power loss issues only [1-2]. The power source of traction system for EV is a limited battery or fuel cell, the investigation of efficiency of overall traction system instead of inverter or motor only, is more meaningful.

In addition, the traction system with an ability of high efficiency during full power range is preferred in EV, especially for direct drive wheel hub motor. However, the efficiency of traction system is relative higher at rate power, which is instinct when it's designed. Therefore, an exploration of advantages of SiC MOSFETs based traction system under low power is more interesting, and which need to be explored nervously.

This paper systematically evaluates the performance of EV traction system based on SiC-MOSFETs and makes a comprehensive comparison between SiC-MOSFETs and Si-IGBTs based traction systems, particularly from efficiency point of view. Both conduction loss and switching loss of SiC-MOSFET are analyzed and modeled taking temperature effect into account. Such methodology yields more accurate prediction of losses. According to the losses, the heat sink of SiC-MOSFETs based inverter is optimal designed, and compared with Si-IGBTs based inverter. Then, both SiC-MOSFETs and Si-IGBTs based experimental benches are built. Experimental results show that the SiC-based traction system has higher system efficiency compared to the Si-based traction system under low power range. And experimental results also verified the losses models of SiC MOSFETs.

2. Inverter Power Losses

In order to show the advantages of SiC-MOSFETs traction system, a quantitative power loss analysis of inverter is obtained based on the primary electrical characteristics parameters. The power loss of an inverter consists of two parts, conduction loss and switching loss. In the calculation, the switching loss of diode is neglected, because it is much smaller comparing to the switching loss of IGBTs or MOSFETs. Although different switch devices are used in the two systems, the calculation methods are identical. Moreover, theoretical loss analysis of Si-IGBTs based inverter was obtained in detail [3]. Therefore, this paper develops the models of conduction loss and switching loss of SiC-MOSFETs. Which yields more accurate prediction of losses thanks to taking temperature effect into account. In this paper, the performance of Cree 1200V 300A SiC MOSFET (CAS300M12BM2) will be investigated and compared with Infineon 600V 300A Silicon IGBT (FF300R06KE3).

2.1. Conduction loss

The conduction loss of SiC MOSFET depends on the on state resistance (RDS(on)) of the MOSFET, thus, the conduction loss expression is:

$$P_{con} = I_{rms}{}^{2} \times R_{DS(on)} \tag{1}$$

Where I_{rms} is average value of the current through the MOSFET, $R_{DS(on)}$ is positive proportional to the temperature. According to characteristics of SiC MOSFETs tested under different temperatures, the quadratic fit curve of $R_{DS(on)}$ is developed. Therefore, the conduction loss of SiC MOSFETs is:

$$P_{con} = I_{rms}{}^{2} \times R_{DS(on)(25℃)}[1 + T_{c1}(T-25) + T_{c2}(T-25)^{2}] \tag{2}$$

2.2. Switching loss

The conduction loss calculation is straightforward by calculating I^2R loss considering temperature effect. However, the switching loss is more complex. Ideal waveforms during the switching transition are shown in Fig. 1. U_{GS} is the voltage across gate to source, U_{DS} is the voltage across drain to source. I_D is the channel current through the SiC MOSFETs.

The switching loss of SiC MOSFETs include two parts, namely turn-on loss and turn-off loss. In terms of the analysis of switching transition as shown in Fig. 1, the switching losses taking temperature effect into account can be expressed as:

$$\begin{aligned} P_{sw} = f_{sw} V_{DS(\max)} I_{D(T)} \times [& (R_{G(T)} + R_{DS(on)(T)}) C_{iss} \left(ln \frac{1}{1 - \dfrac{V_{GS(th)} + \dfrac{I_{DS(MAX)}}{g_{fs}}}{V_{GS}}} - ln \frac{1}{1 - \dfrac{V_{GS(th)}}{V_{GS}}} \right) \\ & + \frac{C_{rss}(R_{G(T)} + R_{DS(on)(T)}) \cdot (V_{DS} - I_D(T) R_{DS(ON)(T)})}{V_{GS} - V_{GS(th)} - \dfrac{I_{DS(MAX)}}{g_{fs(T)}}}] \end{aligned} \tag{3}$$

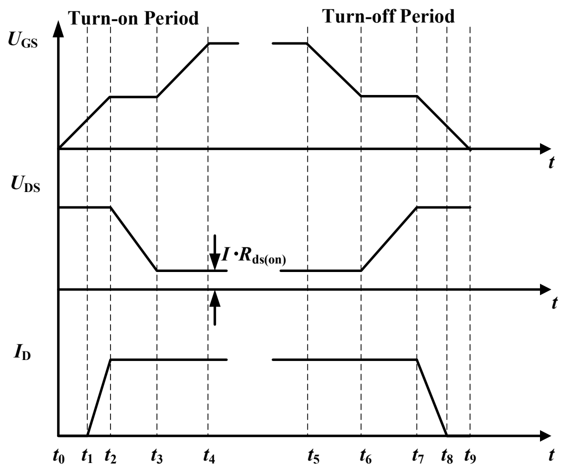


Fig. 1. Ideal switching transition waveforms

According to test results, the switching losses are not sensitive to temperature. The time constant of gate charge-discharge increases while the gate threshold voltage decreases along with temperature rising. Therefore, the switching time is almost invariable and the switching losses remain constant under different temperatures.

3. Inverter Optimal Design

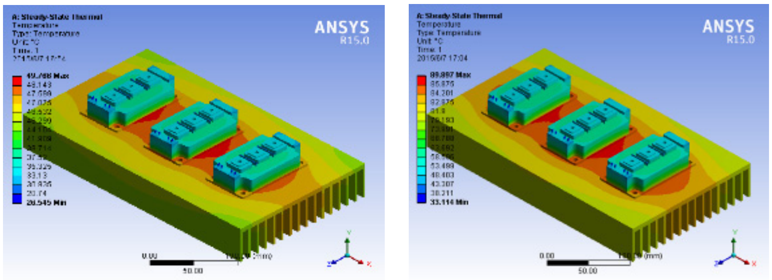
3.1. Thermal analysis and heat sink design

Based on previous analysis, the heat production rate of SiC MOSFET is calculated, and ANSYS Workbench simulation software is used for thermal simulation.

The calculation results of losses under 800 rpm speed and 30 $N \cdot m$ torque are chosen to be analyzed. The simulation results of SiC MOSFETs and Si IGBTs are shown in Fig. 2 respectively. The highest junction temperature of SiC MOSFETs and Si IGBTs are 49.8℃ and 89.9℃ respectively under the same power condition.

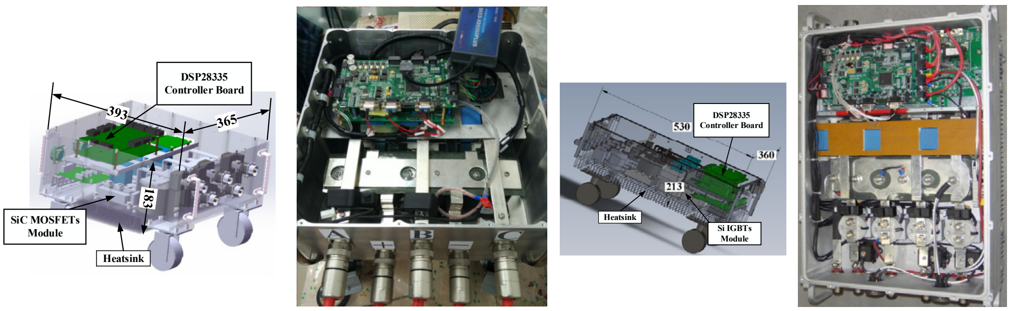
3.2. Inverter design

According to results of thermal analysis, the layouts of SiC-MOSFETs and Si-IGBTs based inverters are optimal designed as shown in Fig. 3. The total weight of SiC-MOSFETs inverter is 16.9kg, while the Si-IGBTs inverter reaches 31.3kg. Therefore, the power density of SiC-MOSFETs inverter is quadruple the Si-IGBTs inverter.



(a) (b)

Fig. 2. Simulation results. (a) SiC MOSFETs (b) Si IGBTs.



(a) (b)

Fig. 3. Prototypes of two inverters. (a) SiC-MOSFETs based inverter; (b) Si-IGBTs based inverter.

4. Experimental Results

To compare the efficiency between SiC-MOSFETs and Si-IGBTs based PMSM drive systems, the test setup is implemented as shown in Fig. 4. Both the SiC-based and Si-based traction systems are powered by an external 270V DC power source and drive a same 3000rpm 30 kW permanent magnet synchronous motor (PMSM) under low speed and light load.

Efficiency comparison at 200 rpm, 400rpm, 800rpm and 1000rpm are shown in Fig. 5. Obviously, SiC-MOSFETs based traction system presents higher efficiency compared with Si-IGBTs based drive at different light loads and low speeds.

The motor efficiency of SiC-MOSFETs system is much higher than Si-IGBTs system at light load thanks to the high switching speed of SiC MOSFETs. Fig. 6 shows that with 20kHz switching frequency there are abundant harmonics in A phase current of Si-IGBTs system while A phase current of SiC-MOSFETs system is almost ideal sinusoidal waveform. It is validated that the current harmonics significantly contribute to the eddy current loss in the PMSM.

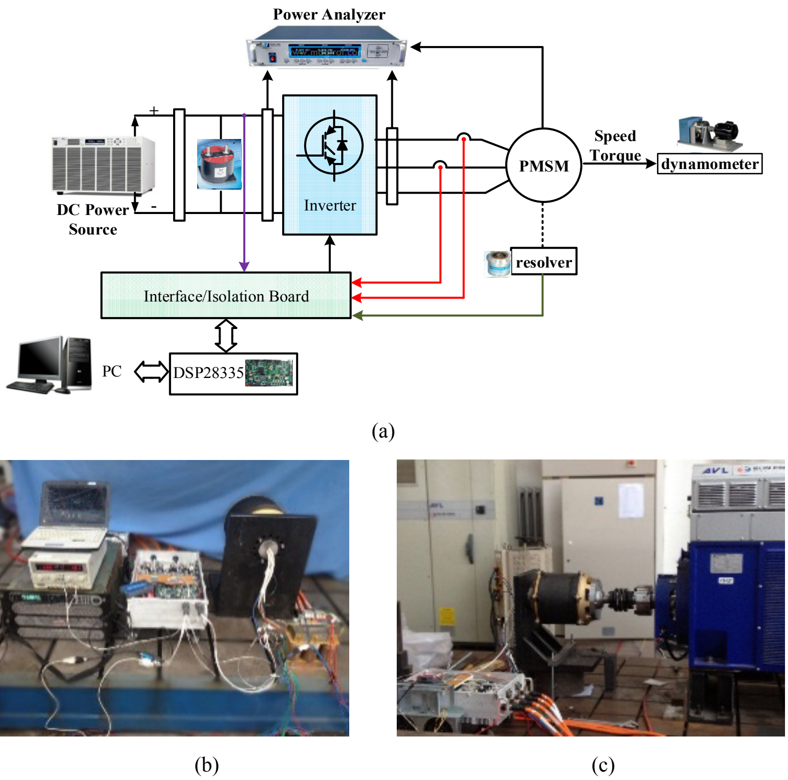


Fig. 4. The test setup. (a) The simplified schematic of test setup. (b) No-load test. (c) On-load test.

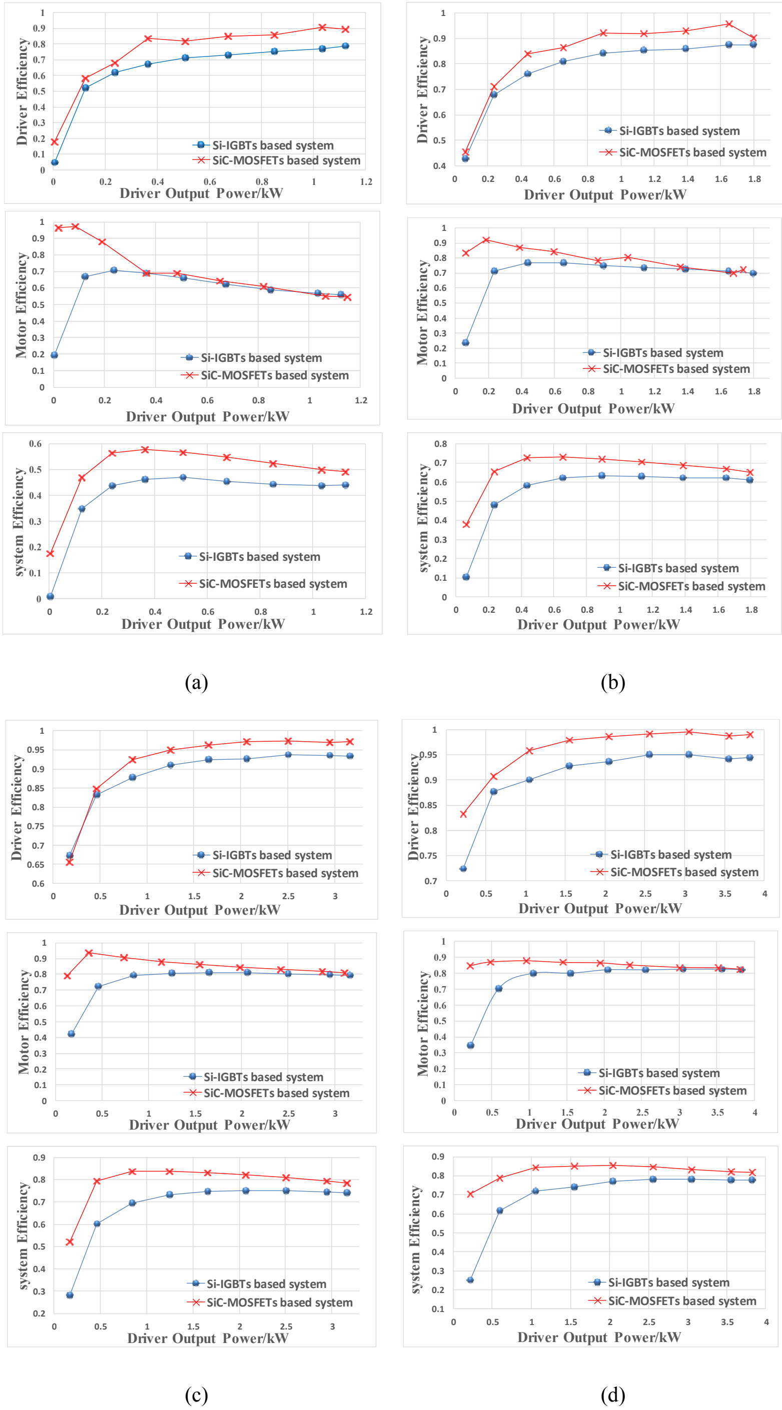
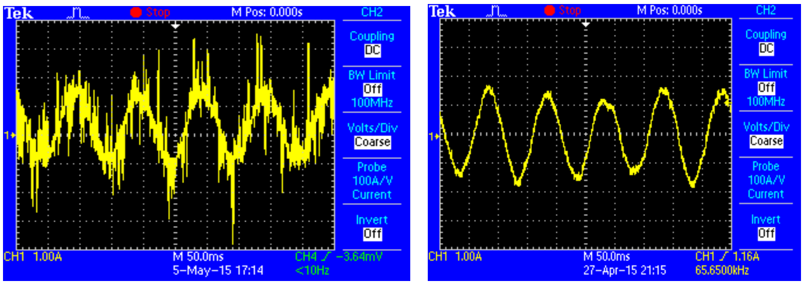


Fig. 5 Efficiency comparison under different speeds. (a) 200rpm; (b) 400rpm; (c) 800rpm; (d) 1000rpm.



(a) (b)

Fig. 6 Current comparison under 200rpm and 0.7 $N \cdot m$. (a) A phase current of Si-IGBTs system; (b) A phase current of SiC-MOSFETs system.

5. Conclusions

This paper discussed the characteristics of EV traction system based on SiC-MOSFETs and compared it with Si-IGBTs based traction systems comprehensively, particularly from efficiency point of view. It's first explored the motor, driven by SiC-MOSFETs based inverter, has extreme high efficiency under low speed and light load. Meanwhile, the inverter efficiency can be increased to more than 99% from around 96% if replacing the Si IGBTs with the SiC MOSFETs. Therefore, the efficiency of overall SiC based traction system is distinctly higher compared with Si based system. In addition, due to the lower losses, the power density of SiC based inverter is quadruple the Si-IGBTs inverter.

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Biography

Xiaofeng Ding received the B.S., M.S., and D.S. degrees in electrical engineering from Northwestern Polytechnical University, Xi'an, China. Since 2012, he is a Lecturer with the Department of Electrical Engineering, Beihang University, Beijing, China. His research interests include permanent magnet machines, motor drives, and silicon carbide (SiC) devices.